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THE ^{54}Mn CLOCK AND ITS IMPLICATIONS FOR COSMIC RAY PROPAGATION AND Fe ISOTOPE STUDIES

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Abstract

Radioactive ^{54}Mn, suggested as a clock for measuring the lifetime of heavy cosmic rays, has a poorly known β-decay halflife estimated to be in the range from $\sim 10^5$ to 10^7 yr. Some years ago Koch et al. concluded from measurements of the Mn/Fe ratio that a significant fraction of low-energy (<1 GeV/nuc) ^{54}Mn produced by Fe fragmentation had decayed. Using a propagation code that includes improved fragmentation cross-sections, and data from HEAO-3 and other spacecraft, we have re-examined the evidence for ^{54}Mn decay. We conclude that present cosmic ray data cannot distinguish the possibility of ^{54}Mn decay in cosmic rays, but point out that this question has important implications for studies of the ^{54}Fe abundance in cosmic ray source material, as well as for cosmic ray propagation studies.

Introduction: Manganese has three isotopes that are either stable or long-lived on cosmic ray time scales. Of these ^{55}Mn is stable, while ^{53}Mn and ^{54}Mn normally decay by electron-capture with halflives of 3.7 x 10^6 yr and 312 days, respectively. In high energy cosmic rays that are stripped of their electrons ^{53}Mn and ^{54}Mn can be considered stable with respect to electron-capture (however, see below), but ^{54}Mn can also decay by either β^+ emission to ^{54}Cr or by β^- emission to ^{54}Fe. The halflives ($t_{1/2}$) for these decays are poorly known; Casse (1973) estimated $t_{1/2} \sim 2\text{x}10^6$yr for β^--decay and $t_{1/2} \sim 10^9$ yr for β^+-decay, while Wilson (1978) estimated that the β^- halflife might range from $6\text{x}10^4$ to 10^7 yr. Recently the laboratory measurement of Sur et al. (1989) established a limit of $t_{1/2}(\beta^+) > 2\text{x}10^7$ yr. and from this and theoretical arguments they deduced a lower limit of $t_{1/2} > 4\text{x}10^4$ yr for the β^- decay mode.

Casse (1973) suggested that ^{54}Mn, a product of Fe fragmentation, might serve as a cosmic ray clock analogous to ^{10}Be, and thereby test whether Fe-group and CNO nuclei have had a similar propagation history. Several years ago Koch et al. (1981) reported that Mn had a significantly flatter energy spectrum than other Fe fragments such as Sc, Ti, V, and Cr. They concluded that the observed Mn/Fe ratio was best explained by energy-dependent decay of ^{54}Mn, with the product $n_H\tau \simeq 0.3$ to 0.6 Myr.cm^{-3}, where n_H is the average hydrogen density in the confinement region and τ is the ^{54}Mn β-decay mean-life. However, Protheroe and Ormes (1983), using different cross sections, found no evidence for ^{54}Mn decay [see also Mewaldt (1981) and discussion therein]. Although the question of ^{54}Mn decay is best addressed with Mn isotope studies, there are to date no cosmic ray observations that resolve ^{54}Mn.

Using available satellite measurements of the elemental composition and a propagation/solar modulation code in conjunction with new, more accurate cross sections, we re-examine the question of ^{54}Mn decay in cosmic rays, and consider its implications.

The Propagation Model: We model cosmic ray composition using a standard energy-dependent "leaky-box" model for cosmic ray propagation in the galaxy, and the "force-field" approximation for solar modulation. The parameters of the model are described in Mewaldt and Webber (1990). The code includes the latest experimental cross section measurements from the UNH group including those for Fe fragmentation, as well as a newly-developed model to predict unmeasured cross sections (Webber 1989).

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Although high energy cosmic rays are generally considered to be fully stripped, there is actually a significant probability for electron attachment, especially at energies below ~0.5 GeV/nuc (see, e.g., Raisbeck 1975). In the case of short-lived nuclei such as ^{54}Mn and ^{55}Fe, this can lead to in-flight electron-capture decay, since the mean time for stripping the electron is ~10^4 yr, much longer than the electron-capture lifetime for these (and several other) species. Our code therefore includes electron pickup and subsequent electron-capture decay, using cross sections estimated from Crawford (1979). With this model we obtain excellent fits to available satellite observations of the "secondary/primary" ratio (Sc+Ti+V)/Fe and to various primary species spanning more than two decades in energy (see Mewaldt and Webber 1990).

Comparison with Cosmic Ray Observations: Figure 1 shows calculated Mn/Fe ratios for three assumed ^{54}Mn β^--decay lifetimes, based on a "solar system" source abundance of $(Mn/Fe)_s = 0.0106$ (Anders and Grevesse 1989), and a density of $n_H = 0.3$ cm^{-3} in the cosmic ray confinement region, as deduced from ^{10}Be and ^{26}Al studies (see summary in Mewaldt 1989). The cosmic ray data in Figure 1 include satellite measurements from HEAO-3, IMP-8, and Voyager-2. Note that 80% to 90% of observed Mn is produced by the fragmentation of Fe.

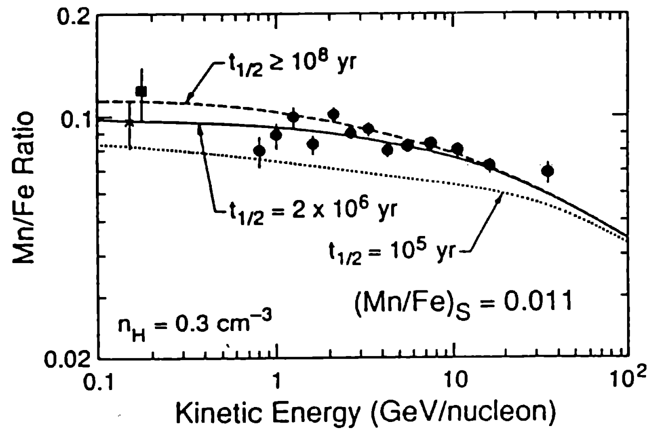

Figure 1: A comparison of measured and calculated Mn/Fe ratios for various assumed ^{54}Mn β^--decay halflives. The calculations assume an interstellar H density of 0.3 cm^{-3}. References to the measurements: circles (Engelmann et al. 1989); square (IMP-8; Simpson 1983); cross (Voyager-2; Ferrando et al. 1989);

A second approach to this problem, shown in Figure 2, uses the ratio of Mn to the Fe-secondaries Sc+Ti+V (Mewaldt 1981), since such "secondary/secondary" ratios are less sensitive to uncertainties in the energy dependence of the pathlength distribution and the Fe total interaction cross section. From Figures 1 and 2 we find that with a Mn source abundance composition equal to that in the solar system, the available cosmic ray data are consistent with $t_{1/2} \simeq 2\times10^6$ yr as found by Koch et al., but inconsistent with halflives as short as 10^5 yr.

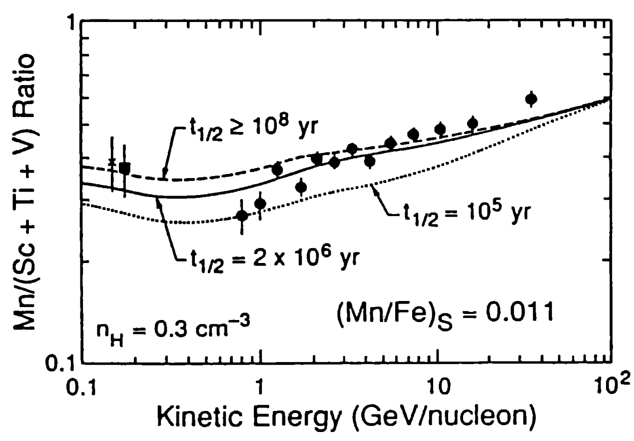

Figure 2: Measured and calculated Mn/(Sc+Ti+V) ratios for various assumed ^{54}Mn halflives. For references to the data see Figure 1.

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However, since the source abundance of Mn is not independently known, we should also consider "non-solar" source abundances of Mn. Figures 3 and 4 demonstrate that by adjusting the Mn/Fe ratio at the source excellent fits can be achieved to the observations for ^{54}Mn β^--lifetimes ranging anywhere from $\sim 10^5$ to $>10^8$ yr. (Note that $t_{1/2} > 10^8$ yr is essentially equivalent to ^{54}Mn stability on cosmic ray time scales.) Of the possibilities in Figures 3 and 4 $t_{1/2} \sim 10^5$ yr provides the best fit, but we consider the entire range of halflives to give an acceptable fit. While these lifetime possibilities might be distinguished by Mn measurements at >50 GeV/nuc (see Figure 4) or by Mn isotope measurements, such data are not now available. We therefore conclude, contrary to Koch et al. (see also Sur et al. 1989), that presently available cosmic ray data cannot distinguish whether any appreciable fraction of ^{54}Mn undergoes β-decay in cosmic rays (see also Mewaldt 1981).

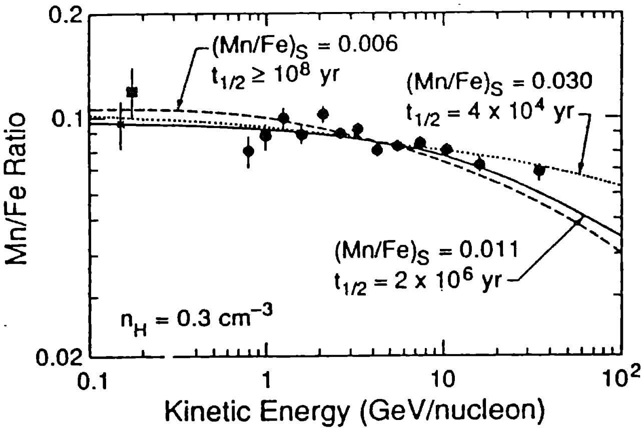

Figure 3: Measured and calulated Mn/Fe ratios as in Figure 1, except that the source abundances of Mn have been adjusted as indicated to fit the observations (see also Figure 3).

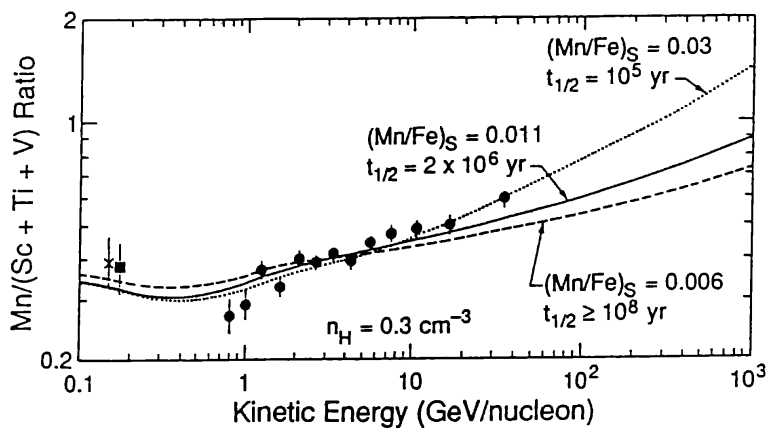

Figure 4: Measured and calulated Mn/(Sc+Ti+V) ratios as in Figure 2, except that the source abundances of Mn (in the form of ^{55}Mn) have been adjusted as indicated to fit the observations.

Implications for Fe Isotope Studies: Because the β^- decay of ^{54}Mn produces ^{54}Fe, interpretations of this interesting Fe isotope in cosmic rays are subject to the uncertainties in ^{54}Mn decay discussed above. Figure 5 shows the calculated dependence of the ^{54}Fe/^{56}Fe ratio on the assumed ^{54}Mn β^--decay halflife. Note that for an assumed solar system source composition (^{54}Fe/^{56}Fe = 0.063) the resulting ^{54}Fe/^{56}Fe ratio at 1 AU can vary from <0.08 to >0.10; at present this entire range is consistent with existing cosmic ray Fe isotope studies (see, e.g., Grove et al. 1990). To our knowledge, this complication to Fe isotope studies has not been pointed out previously. It is clear that future studies of Fe isotopes should at the same time measure the isotopic composition of Mn.

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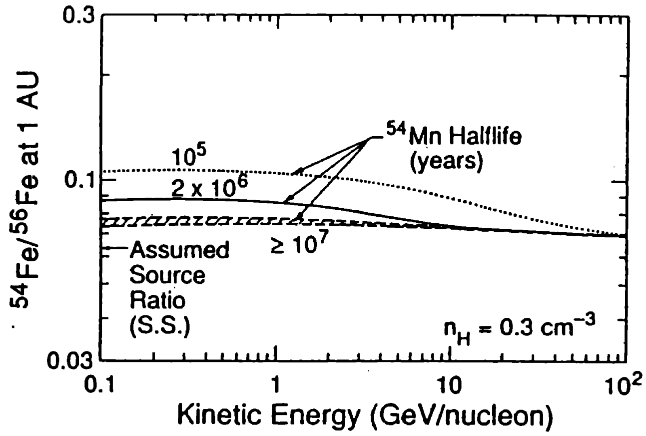

Figure 5: Expected $^{54}Fe/^{56}Fe$ ratio for various assumed ^{54}Mn β-decay halflives. The calculations assume a solar system (S.S.) source ratio as indicated.

Conclusions: In summary, we conclude that the role of ^{54}Mn decay in cosmic rays is unlikely to be understood by elemental composition measurements such as those considered here; rather, precise measurements of the isotopic composition of cosmic ray Mn will be required. Even then, it appears unlikely that ^{54}Mn can achieve its potential as a cosmic ray clock until either its β-decay lifetime is established independently, or its isotopic composition in cosmic rays is measured over a broad energy interval. The latter objective is possible with a combination of low-energy isotope measurements planned for Ulysses, CRRES, SAMPEX, WIND, and Geotail, along with high energy measurements planned for Astromag.

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